

LOW COST HEAT TREATMENT PROCESS FOR PRODUCTION OF DUAL MICROSTRUCTURE SUPERALLOY DISKS

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INTRODUCTION

There are numerous incidents where operating conditions imposed on a component mandate different and distinct mechanical property requirements from location to location within the component. Examples include a crankshaft in an internal combustion engine, gears for an automotive transmission, and disks for a gas turbine engine. Gas turbine disks are often made from nickel-base superalloys, because these disks need to withstand the temperature and stresses involved in the gas turbine cycle. In the bore of the disk where the operating temperature is somewhat lower, the limiting material properties are often tensile and fatigue strength. In the rim of the disk, where the operating temperatures are higher than those of the bore, because of the proximity to the combustion gases, resistance to creep and crack growth are often the limiting properties.

Advanced nickel-base superalloys have been introduced recently that should improve engine performance through higher disk temperatures as compared to current engines. This is achieved by using alloy compositions with high levels of gamma prime and refractory elements.

However, there is a longer term need for disks with even higher rim temperature capabilities of 1400F or more. This increased temperature capability would allow higher compressor exit temperatures thereby increasing the efficiency of the gas turbine engine. The increased temperature capability of the rim could be achieved, in part, by utilizing disks with a coarse grain microstructure in the rim, which yields optimal creep resistance, and a fine grain microstructure in the bore, which yields optimal fatigue resistance (Ref. 1).

For most gas turbine applications, nickel-base superalloy disks are currently heat treated at a uniform solution temperature either below the gamma prime solvus temperature (subsolvus heat treatments), or above the solvus temperature (supersolvus heat treatments). Several recent approaches have been established which differ from the traditional subsolvus or supersolvus heat treatment. One approach, more fully described in U.S. Patent 5,312,497, uses induction heating to preferentially heat the rim of a disk, while a pressurized gas is run through the bore of the disk to keep the bore and web cooler. Another approach, more fully described in U.S. Patent 5,527,020, uses top and bottom thermal caps placed over the bore of the disk to blow pressurized air through the center of a single disk, while the disk is being held at a constant temperature in a gas-fired furnace. In this way, the bore of the disk is maintained at a sufficiently cooler temperature than the rim of the disk, thus, achieving the desired subsolvus solution of the bore, with a fine grain microstructure, and the desired supersolvus solution of the rim, with a coarse grain microstructure.

While each approach produces the desired dual microstructure in the disk, fine grain bore and coarse grain rim, they both add to the cost and complexity of the solution heat treatment. The approaches described in U.S. Patents 5,312,497 and 5,527,020 can only be applied to one

disk at a time, and are thereby very expensive. The practice of U.S. Patent 5,527,020, while having reduced complexity compared to the practice of U.S. Patent 5,312,497, still requires specialized air pressure lines going into a furnace that must remain operable for process viability. Accordingly, there still remains a need to provide heat treatment technology that produce different microstructures in the bore and rim of nickel-base superalloy disks without suffering the drawbacks of the previous approaches.

The primary object of this paper is to present and demonstrate the viability of a new solution heat treatment technology which can be used to produce nickel-base superalloy disks with a fine grain bore and coarse grain rim, and accomplish such by the use of standard gas-fired production furnaces without auxiliary cooling. It is further desired to provide the differential microstructures in the rim and bore of nickel-base superalloy disks while still maintaining the option for rapid cooling upon completion of the solution heat treatment with minimal delay in transferring the disk from the furnace to the fan or oil quenching station.

BRIEF DESCRIPTION OF THE DUAL MICROSTRUCTURE HEAT TREATMENT TECHNOLOGY

The basic concept of the Dual Microstructure Heat Treatment (DMHT) technology described in this paper utilizes the natural thermal gradient between the bore and rim of a disk during the initial phase of conventional heat treatments. When a cold disk is inserted into a typical production furnace the outer skin of the disk becomes hot while the interior remains cool for a significant period of time. By enhancing/modifying the thermal gradient with heat sinks, it

is possible to design a solution heat treatment which can produce a fine grain bore and coarse grain rim in a typical turbine disk. The heat sinks are nothing more than solid metal cylinders, termed thermal blocks, which have large thermal mass that chill the central portion of the disk. In general, the thermal blocks will have a diameter which is less than that of the disk being heat treated. Two thermal blocks are utilized, one on the top face and one on the bottom face of the disk. This arrangement provides direct exposure of the rim to the radiant energy of the furnace while shielding the bore of the disk. To enhance the effectiveness of the thermal blocks an insulating jacket may also be employed to slow the temperature rise of the thermal blocks. The insulation is applied to all surfaces of the thermal blocks which are exposed to the furnace, while a clean, metal-to-metal contact is desired between the disk and the thermal blocks.

To perform the desired heat treatment, the disk and the heat sinks are placed in a standard production furnace maintained at a temperature above the solvus of the disk alloy, and removed when the rim of the disk exceeds the solvus but before the bore has reached the solvus temperature of the disk alloy. As one might expect, timing of the DMHT process is critical to the success of this approach. While modeling the transient thermal behavior of the disk and heat sinks is desirable, a more practical approach is to monitor the temperature of the thermal block near the bore of the disk with an embedded thermocouple. When the thermocouple reaches a predetermined temperature below the solvus of the disk alloy, the disk and heat sinks are pulled from the furnace. As the heat sinks are simple, compact assemblies, the disk and the heat sinks can be easily separated after removal from the furnace and the disk can be quenched with minimal delay.

FINITE ELEMENT ANALYSIS OF THE DMHT PROCESS

Before the actual DMHT trials can be performed, the shape and size of the heat sinks must be established and the heat treatment parameters must be determined. This is most readily accomplished using any commercially available finite element computer package. The analysis in this paper was performed using ALGOR's finite element computer package, which has a transient thermal analysis module.

The disk used in this paper is illustrated in Figure 1. It is representative of a typical disk shape, having a thick bore with a central hole and a thinner rim. Thermal blocks of varying dimensions were analyzed in an attempt to obtain the desired thermal gradient for this disk in a reasonable time. Thermal blocks measuring 6" in diameter and 2" thick were found to be satisfactory for this purpose. The results of the analyses obtained after a given time at 2150F are presented in Figures 2 and 3 for thermal blocks without and with insulation respectively. Values for density, conductivity, and heat capacity for the disk and thermal blocks in these analyses were 0.3 LB/IN³, 1.0 BTU/HR-IN-F, and 0.2 BTU/LB-F respectively. The effective heat transfer coefficient of the metallic surfaces was assumed to be 0.5 BTU/HR-F-IN² while the insulated surfaces were assumed to block all heat transfer. Comparing Figures 2 and 3, one can see the advantage of insulating the thermal blocks. These two cases serve as upper and lower bounds for the experimental DMHT trials run in this program. The temporal evolution of temperature at the ID and OD of the disk are presented in Figure 4 for the insulated heat sinks. The shaded region in Figure 4 represents an estimated time interval for creation of an acceptable dual grain macrostructure for a disk alloy with a 2100F solvus temperature.

DMHT TRIALS

While modeling of the DMHT process can provide valuable insight and guidance, estimates of the thermal gradients are only as reliable as the material properties and process boundary conditions which go into these analyses. For this reason, a DMHT trial on a thermocoupled disk with insulated heat sinks was performed to validate the modeling effort and establish the exact configuration and parameters for the DMHT process.

The disk and heat sink configuration for this first DMHT trial is shown in Figure 5. The disk shape is identical to that shown in Figure 1. As seen in Figure 5, 6" diameter thermal blocks made from plain carbon steel bar stock were used. The thermal blocks have small alignment pins which fit in the bore hole of the disk. This insures that the disk and thermal blocks remain concentric throughout the heat treatment. The thermal blocks were insulated by building insulating jackets which were filled with Kaowool™, as shown in Figure 5. The outer shells of the insulating jackets were fabricated from sections of an 8" diameter steel pipe. The upper shell rests on the disk, while the lower shell is cut to a length which leaves a tiny gap between the disk and the shell. This assures that that the lower thermal block and the disk maintain maximum thermal contact. Both of the thermal shells are positioned with 8" diameter alignment plates, which are bolted to the thermal blocks. This maintains concentricity of the insulating jackets, the thermal blocks, and the disk. Thermocouples were also embedded in the disk and heat sink for this trial as shown in Figure 6.

The disk and heat sinks were then placed in a gas-fired furnace at 2000F. For this trial the furnace temperature was intentionally set below the solvus temperature of the disk alloy to allow several DMHT trials to be run, if needed, without producing any significant grain growth in the disk. The time-temperature response of the thermocouples is plotted in Figure 7. These data clearly show that a significant temperature gradient can be maintained between the bore and rim of the disk and suggest that there is sufficient lag time to allow coarsening of the grain size in the rim while maintaining a fine grain size in the bore. Further the temperature in the heat sink is almost equivalent to the bore temperature of the disk near the end of the run. This will provide a simple and reliable method to determine the time at which the disk and heat sinks should be removed from the furnace.

After reviewing the data from the first DMHT trial and the finite element analyses, it was decided that a DMHT conversion would be attempted at a furnace temperature above the gamma prime solvus of the disk alloy. If successful, this would produce a disk with a coarse grain microstructure in the rim and a fine grain microstructure in the bore. Several additional forgings, with fine grain microstructures, were machined to the disk shape shown in Figure 1. In the first DMHT conversion attempt, a furnace temperature of 2140F was tried with the heat sink assembly shown in Figure 5. A single thermocouple was embedded in the upper thermal block to monitor temperature response near the bore of the disk. The disk and heat sink were removed from the furnace when the thermocouple in the upper thermal block reached 2070F. The disk and heat sink were allowed to cool in still air. The resulting macrostructure revealed a narrow band on the outer periphery of the disk which was converted to a coarse grain microstructure while the remainder of the disk retained a fine grain microstructure.

Based on these results, a second DMHT conversion was attempted. In this trial the furnace temperature was increased to 2170F and the disk and heat sink assembly were removed from the furnace when the thermocouple in the upper thermal block reached 2100F. The disk was also quenched in oil with a total transfer time from furnace to quench tank of less than one minute. This included removal of the heat sinks. The resulting macrostructure and microstructures are shown in Figures 8 and 9. As seen in these figures, a band over 2" wide on the outer periphery of the disk was converted to a coarse grain microstructure while the interior of the disk retained a fine grain microstructure. Further, no quench cracks were observed in the disk.

SUMMARY AND CONCLUSIONS

A new solution heat treatment technology, termed Dual Microstructure Heat Treatment (DMHT), has been developed and demonstrated which can be used to produce nickel-base superalloy disks with a fine grain bore and coarse grain rim. The DMHT process requires nothing more than two relatively simple heat sinks, on the top and bottom of the disk to be heat treated, and can be performed using standard gas-fired production furnaces without auxiliary cooling. Further, the heat sinks are easy to remove thereby allowing rapid quenching of the disk with minimal delay.

Continued development and evaluation of the DMHT technology is planned. Areas to be investigated include refinement of models for the DMHT process, assessment of mechanical

properties of DMHT disks, and continued development of the DMHT technology from a production and cost standpoint.

ACKNOWLEDGEMENT

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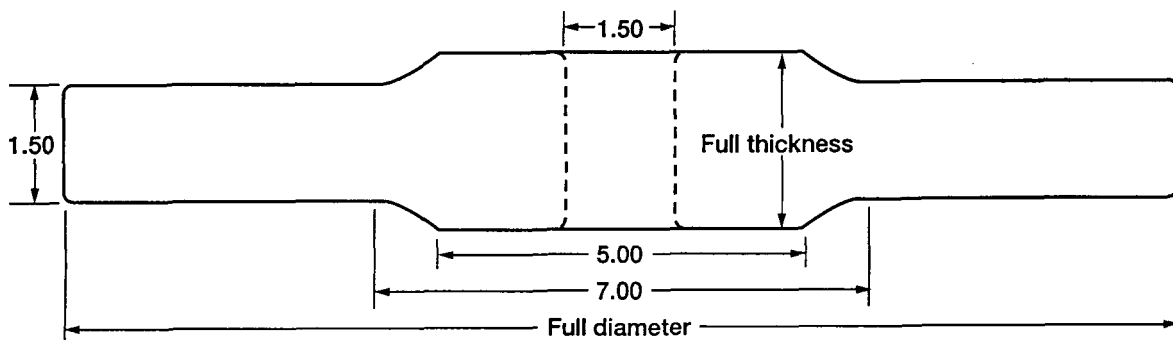


Figure 1.—Machining plan for superalloy disk (13-in. diameter × 2-in. thick forging).

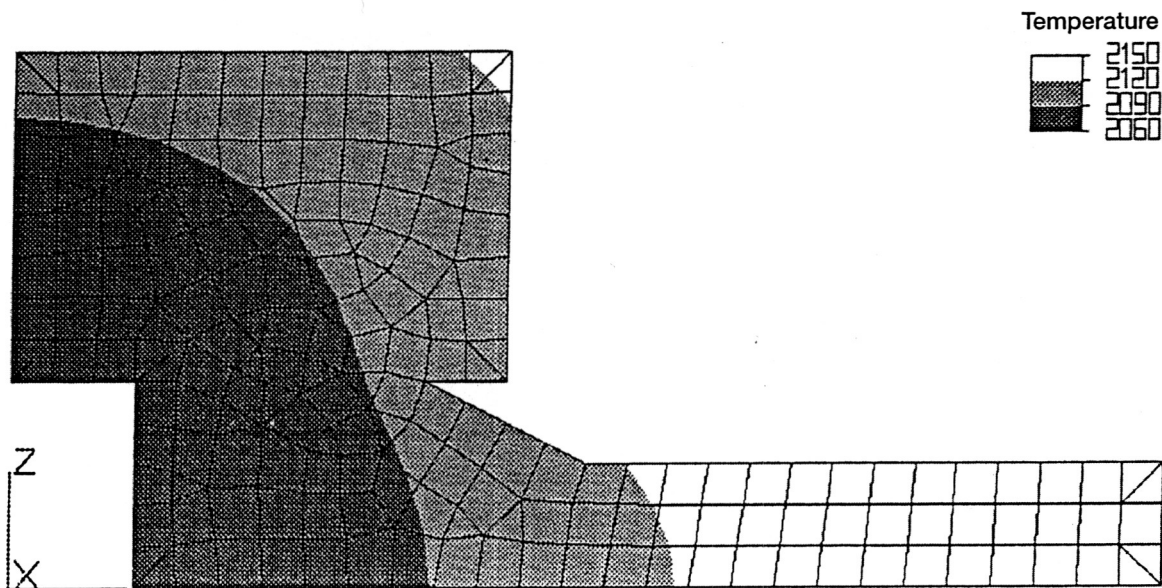


Figure 2.—Thermal gradient with no insulation at 0.6 hr.

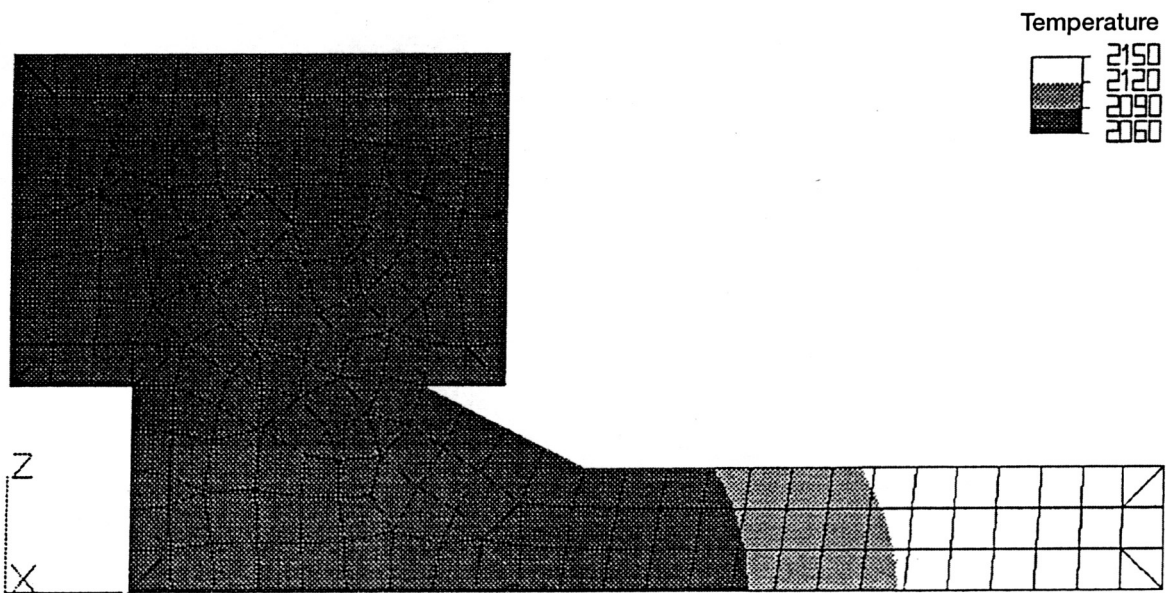


Figure 3.—Thermal gradient with insulated thermal block at 1.5 hr.

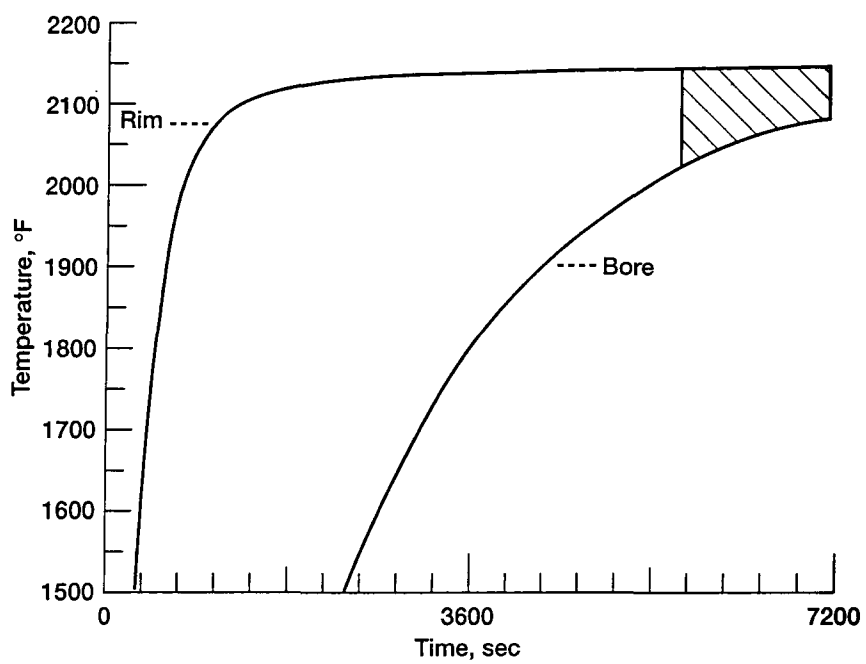


Figure 4.—Predicted evolution of rim and bore temperatures.

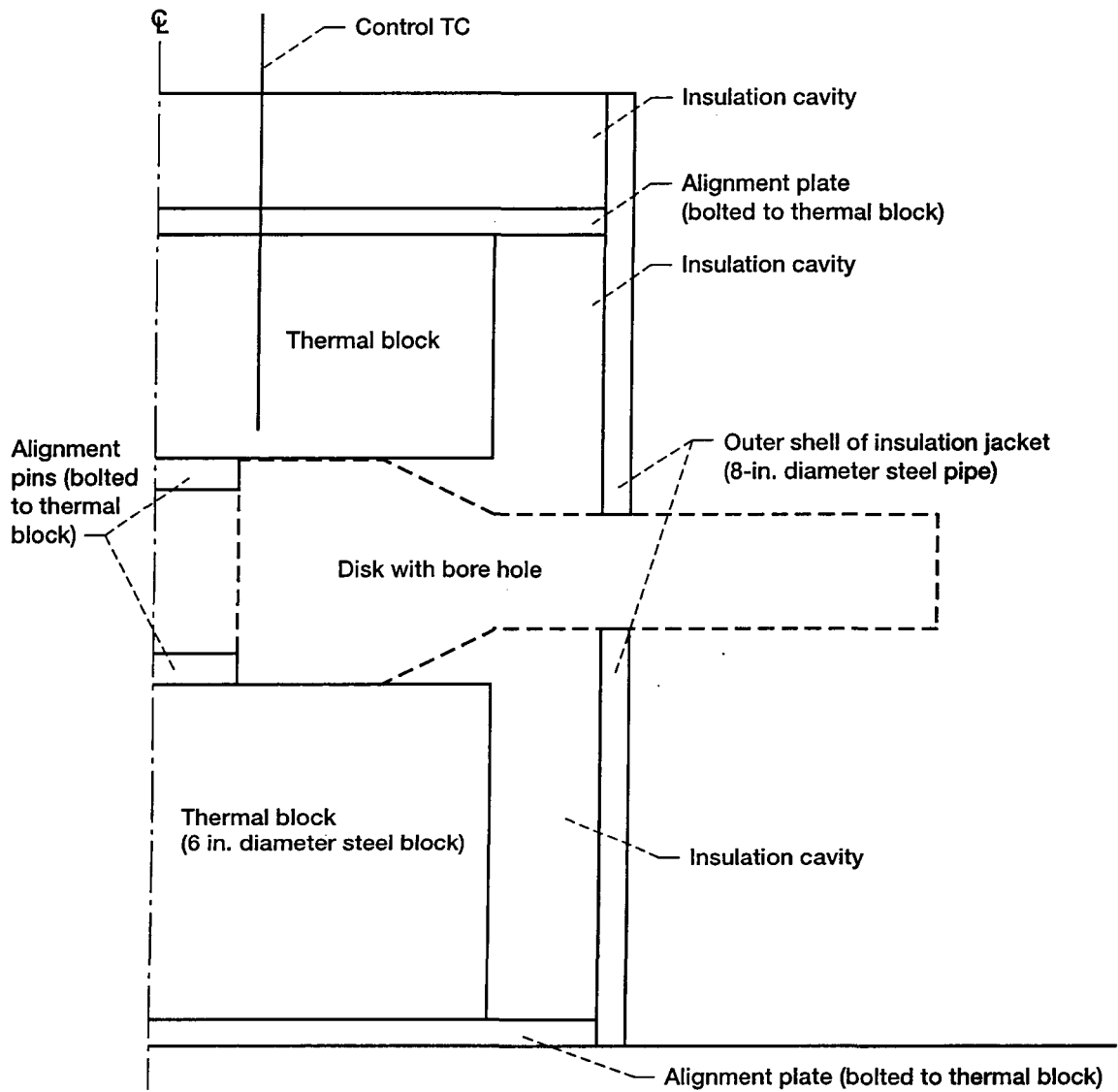


Figure 5.—Schematic diagram of the disk and heat sinks.

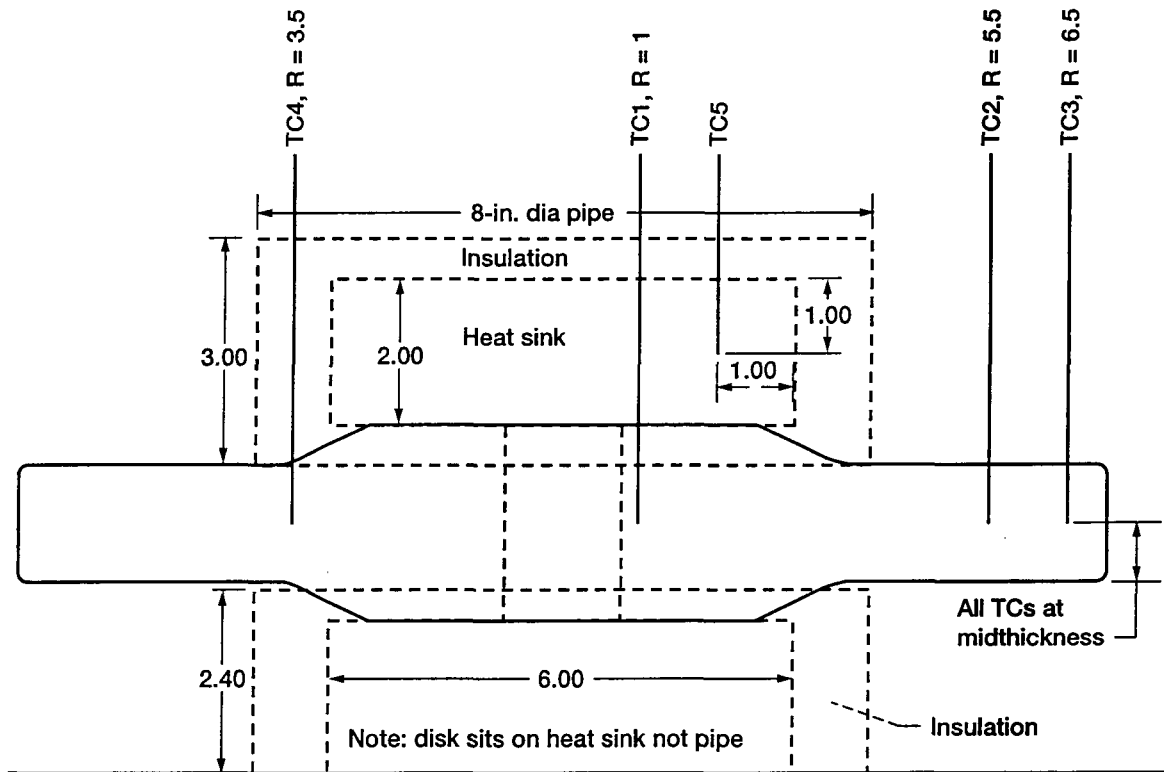


Figure 6.—Thermocouple location for first DMHT trial.

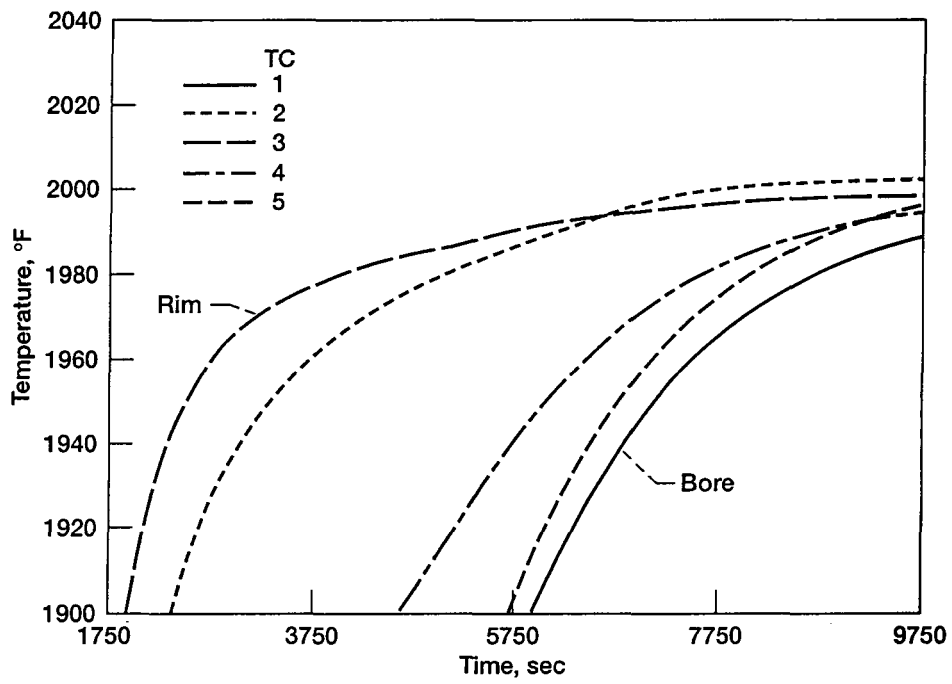


Figure 7.—Thermocouple data for first DMHT trial.

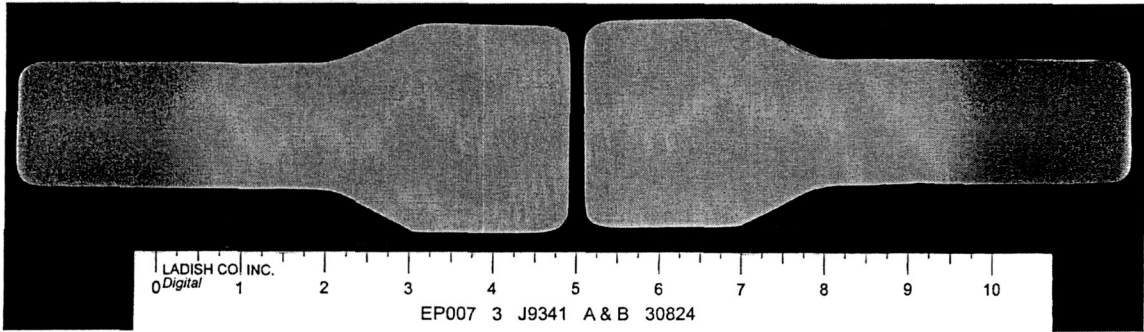
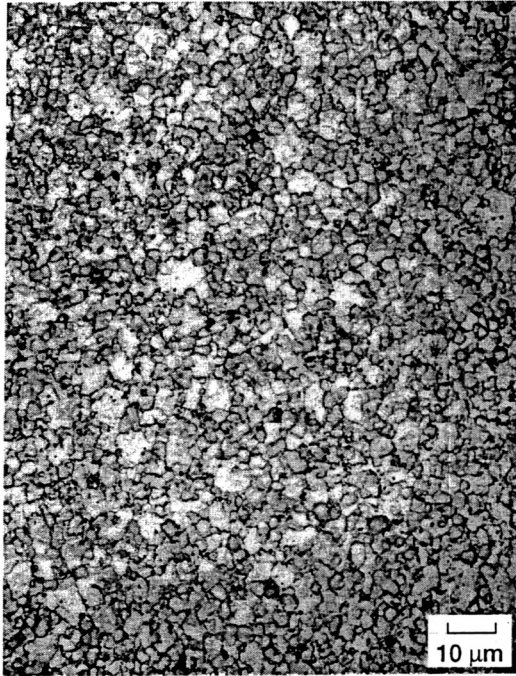


Figure 8.—Macrostructure for second DMHT conversion.



Bore



Rim

Figure 9.—Bore and rim microstructure after DMHT conversion.